VTT Technical Research Centre of Finland

Identifying crashes potentially affected by conditionally automated vehicles in Finland

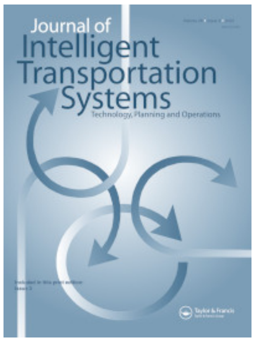
Malin, Fanny; Silla, Anne; Mesimäki, Johannes; Innamaa, Satu; Peltola, Harri

Published in:
Journal of Intelligent Transportation Systems: Technology, Planning, and Operations

DOI:
10.1080/15472450.2022.2074793

E-pub ahead of print: 20/05/2022

Document Version
Publisher's final version



Taylor & Francis
Taylor & Francis Group

Journal of Intelligent Transportation Systems
Technology, Planning, and Operations

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gits20

Identifying crashes potentially affected by conditionally automated vehicles in Finland

Fanny Malin, Anne Silla, Johannes Mesimäki, Satu Innamaa & Harri Peltola

To cite this article: Fanny Malin, Anne Silla, Johannes Mesimäki, Satu Innamaa & Harri Peltola (2022): Identifying crashes potentially affected by conditionally automated vehicles in Finland, Journal of Intelligent Transportation Systems, DOI: 10.1080/15472450.2022.2074793

To link to this article: https://doi.org/10.1080/15472450.2022.2074793

JOURNAL OF INTELLIGENT TRANSPORTATION SYSTEMS
https://doi.org/10.1080/15472450.2022.2074793

Identifying crashes potentially affected by conditionally automated vehicles in Finland

Fanny Malin, Anne Silla, Johannes Mesimäki, Satu Innamaa, and Harri Peltola

VTT Technical Research Centre of Finland Ltd, Espoo, Finland

ABSTRACT

The objective of the study was to identify the number and national fraction of crashes that could be affected by universal adoption of conditionally automated vehicles (SAE3) based on the expected number of injury crashes, fatalities, and serious injuries in Finland. The study considered passenger cars with automated driving systems (ADS) for motorways and urban areas. The results show that of the national annual average, the motorway ADS has the potential to affect at maximum 3.3% of injury crashes, 3.1% of fatalities, and 3.2% of serious injuries. The corresponding fractions for urban ADS in the four largest Finnish cities were: 2.2%, 1.1% and 2.5%. Of the cities' annual average, urban ADS has the potential to affect at the most 17.4% of injury crashes, 17.1% of fatalities, and 26.8% of serious injuries. Although the market introduction of these ADS is on the horizon, deployment can be expected to be slow, indicating a need for additional measures to reach the traffic safety goals.

ARTICLE HISTORY

Received 27 April 2021
Revised 25 April 2022
Accepted 4 May 2022

KEYWORDS

Automated driving; Empirical Bayes method; killed and seriously injured

Introduction

The European target to halve by 2020 the number of road traffic fatalities that occurred in 2010 is highly unlikely to be reached, as the latest available statistics show the average reduction from 2010 to 2018 to have been a mere 21% (EC, 2020a). In 2017, the same target was reaffirmed for 2030 with respect to 2020, this time including also serious injuries (Valletta Declaration on Road Safety, 2017). Developments in sensor and camera technologies have produced Advanced Driver Assistance Systems (ADAS) to assist drivers with driving and parking tasks. Some ADAS, such as Intelligent Speed Adaptation (ISA) and Autonomous Emergency Braking (AEB), can even intervene in the driving task if necessary. A growing number of ADAS are already appearing in today's vehicles, either as factory fit or retrofit, some of which will become mandatory in new vehicles in 2022 (Scholliers et al., 2020). Based on several estimates, ADAS have helped reduce traffic crashes and have great potential to further improve traffic safety (Furlan et al., 2020; Scholliers et al., 2020).

In addition to the development of ADAS, technological advances in sensor, communication, and computing technologies have enabled vehicles to become automated, i.e., able to take over part of the driving task. Automation of road traffic has been proposed as one way to improve traffic safety (EC, 2020a, 2020b; Fagnant & Kockelman, 2015; Milakis et al., 2017; Noy et al., 2018), but these effects of higher automation are still largely unexplored compared to ADAS. Automated vehicles (AV) can be categorized based on the level of automation and degree of connectivity. Level of automation refers to the degree of human involvement in the driving task. The Society of Automotive Engineering's (SAE) International Classification (SAE International, 2021) includes six levels: SAE0, no driving automation; SAE1, driver assistance; SAE2, partial driving automation; SAE3, conditional driving automation; SAE4, high driving automation; and SAE5, full driving automation. Here we refer to higher automation as SAE levels 3–5.

Automated passenger cars currently under development are conditionally automated, meaning manually driven vehicles with automated driving systems (ADS) for different environments (e.g., highway pilot) or driving tasks (e.g., parking pilot) (ERTRAC, 2017). In conditionally automated vehicles (SAE3), the user is still required to take over the driving task if the

CONTACT Fanny Malin fanny.malin@vtt.fi VTT Technical Research Centre of Finland Ltd, Espoo 02044, Finland.

system cannot handle the situation. Furthermore, they can operate only within their operational design domain (ODD), which can include requirements related both to infrastructure (e.g., road type, lane markings, quality of infrastructure) and to current conditions (e.g., traffic situation, weather). The vehicle's advanced ADS-related equipment can enable ADAS support for manual driving.

Due to the incomplete readiness of the technology, the availability of real-world test results on the safety impacts of higher automation is limited. Some studies (Favaró et al., 2017; Wang & Li, 2019; Ye et al., 2021) have analyzed crashes involving automated vehicles on public roads in California. However, common to these is a small sample size ($n = 26$–133), focus on suburban roads, study vehicles originating from only a few car manufacturers, and Google accounting for most of the reports.

This paucity of information on the involvement of AVs in crashes means that their safety effects have been gleaned from alternative methods, such as a multi-agent traffic simulation (Kitajima et al., 2019), a simulation-based surrogate safety measure approach (Morando et al., 2018, Papadoulis et al., 2019, Virdi et al., 2019), virtual scenario-based experiments using Monte-Carlo techniques (Wang et al., 2017), and retrospective analysis of crash data (Combs et al., 2019; Utriainen, 2021; Utriainen & Pöllänen, 2020). Scanlon et al. (2021) found with counterfactual simulation of 72 historic crashes that the Waymo ADS avoided all crashes when it was set as the initiator vehicle, and that a majority of crashes (82%) were avoided and 10% mitigated when it was set as the responding vehicle. Furthermore, most studies lack guideline-compliant descriptions of the system (e.g., SAE level of automation, type of vehicle) and ODD (e.g., road type, limiting road and weather conditions) (ERTRAC, 2017; Innamaa et al., 2018). Rösener (2020) combined multiple methods (traffic simulations, crash re-simulations and crash data) to assess the safety impacts of ADS in Germany. According to his results, a Motorway Chauffeur (passenger car; SAE3; operating on motorways and separated roads; speed up to 130 km/h; no heavy precipitation (snow/rain) or fog; no icy conditions; no construction sites) could potentially affect 3% of all injury crashes in Germany (2016), whereas an Urban Robo-Taxi (passenger car; SAE4; all urban streets, speed up to 50 km/h; no other limitations) could potentially affect 46%. With a penetration rate of ADS in use of 50%, the reduction of all injury crashes would be 2% for the Motorway Chauffeur and 17% for the Urban Robo-Taxi. Rösener (2020) did not consider the potential impacts of ADAS enabled beyond the ODD of ADS due to the availability of advanced sensors. Bjorvatn et al. (2021) combined multiple methods (traffic simulations, crash re-simulations, and crash data) to assess traffic safety impacts of ADS (SAE3) for passenger cars on motorways and in urban areas for EU27 + 3 level (EU27, UK, NO & CH) within the European L3Pilot project. According to their results, of all injury crashes in the EU27 + 3, a motorway ADS (passenger car; SAE3; operating on all motorways and separated roads; speed up to 130 km/h; no heavy precipitation (snow/rain) or fog; no icy conditions) could potentially affect at maximum 4% and urban ADS (passenger car; SAE3; major urban streets, speed up to 50 km/h; no heavy precipitation (snow/rain) or fog; no icy conditions; no construction sites) could potentially affect 40%. When taking into account the systems' effectiveness and penetration rates 5–30%, they concluded that all injury crashes can be reduced by 0.1–1.2% with motorway ADS and 0.8–10.2%, with urban ADS (the smaller number representing a 5% penetration rate and the higher a 30% penetration rate). Furthermore, Bjorvatn et al. (2021) concluded that all crashes on motorways can be cut by 2.0–19.0% and that crashes occurring in conditions fulfilling the ODD requirements can be cut by 3.8–27.6% by the motorway ADS.

Many of the aforementioned studies relied on crash data to evaluate the traffic safety aspects of automated vehicles. Crash data are, however, subject to shortcomings, primarily underreporting and random variation (Elvik et al., 2009, p. 74; Yannis et al., 2014). Rather than recorded numbers of crashes, expected numbers (i.e., long-term average number of crashes per time unit expected to occur with unchanged exposure and crash rate) are a better measure for estimating the safety at a specific location, as this eliminates the random variation of crash records (Elvik, 2008; Elvik et al., 2009, p. 74–75, Hauer et al., 2002). It is especially important when investigating crash severities separately, which requires splitting crash records into even smaller groups. The expected number of crashes is calculated with the Empirical Bayes (EB) method by combining crash records with a crash prediction model, and it is one of the standard approaches to evaluating safety effects (Elvik, 2008). No studies were found that used the expected number of crashes to evaluate the safety potential of AVs.

In Finland, the TARVA tool has been under continual development since 1994 for predicting traffic safety and estimating the effects of individual or

Table 1. Description of ADS under assessment.

ODD requirements	Motorway ADS	Urban ADS
Infrastructure	- All motorways and other dual carriageway roads, i.e., physically separated driving directions. - Visible lane and road markings are needed on both sides (small gaps are manageable). - ODD begins when the vehicle has merged onto the motorway from the on-ramp and ends when the vehicle merges with the off-ramp or leaves the motorway. - ODD includes weaving areas without ramps and road works but not toll station areas.	- Urban streets with a speed limit of 50 km/h or under. - On streets with oncoming traffic, the street width must be sufficient for two cars to pass each other. - Lane separators such as curbs or lane markings are needed on one side (small gaps are manageable). - ODD includes signalized and non-signalized intersections, simple roundabouts (one driving lane and no bicycle lane) and signalized tramway/railway crossings but not roadwork areas.
Road and weather conditions	- ODD covers clear, cloudy and light rain, dry and moist road conditions and all lighting conditions. - It excludes all extreme weather conditions (e.g., hard rain, snowfall, slush) and road conditions (e.g., icy, snowy, slushy and standing water).	

combined safety measures. The tool uses the EB method (Peltola et al., 2013). In 2018, serious injuries (MAIS3+) were included in the tool, and the approach to calculating crash prediction models was updated as a result (Peltola et al., 2019) from that described by Peltola et al. in 2013. The current models have a traffic volume-dependent crash risk rather than assuming it to be constant throughout the road section. The tool covers the entire highway network (around 78,000 km) and can estimate the expected number of injury crashes, fatalities, and serious injuries (MAIS3+) for any selected road section. The street network (about 26,000 km) is administered by the municipal government and is not included in the tool, since there has generally been a shortage of traffic data, data harmonization, and interest in funding for development of the TARVA tool for urban areas. However, municipalities have recently started collecting and publishing traffic-related data. Despite the potential of this data to deepen our knowledge of current traffic safety in urban areas, for example in relation to serious injuries (Malin et al., 2020) and overall safety development (Elvik, 2010), it has yet to be examined with statistically sound methods.

The main objective of this study was to identify to what extent passenger cars with ADS (SAE3) for motorways and urban areas can improve traffic safety in Finland. The methodological focus is on reliably identifying the systems' target crashes, i.e., the maximum number and national fraction of crashes that could potentially be prevented or mitigated if their penetration rate was 100% and if their use could prevent all crashes.

As opposed to previous similar research activities relying on retrospective analysis of crash statistics, this study derives from identifying the road network where ADS can be used, and it models the current safety situation using the EB method, thus enabling a detailed and methodologically sound analysis (Elvik, 2008) per severity (injury crashes, fatalities, and serious injuries). To model all road networks similarly, the methodology of Peltola et al. (2013, 2019) was first further developed and extended to cover also urban areas. Second, the crashes potentially affected by ADS were identified by applying the information on detailed system and ODD descriptions developed as part of the European L3Pilot project. Finally, the potentially affected crashes were extended to include active safety systems remaining enabled when the ODD requirements of ADS are not fulfilled. Specifically, the study was limited to AEB and electronic stability control (ESC), since these are intervening active systems and do not require a reaction or intervention from the driver. The results of our study provide information on the maximum potential of conditionally automated vehicles to help reach traffic safety goals.

Method

Description of systems under assessment

The assessment began with the definition of systems, as detailed descriptions are required for identifying road networks inside and outside the ODD. Also, any restrictions related to the system should be known in order to identify limiting conditions. The ADS descriptions used here were based on the mature system descriptions developed within the European L3Pilot project (Metz et al., 2019, pp. 22–25) and the ODD requirements of these ADS are summarized in Table 1. These are theoretically defined in terms of the system's ODD requirements for infrastructure and occurring conditions and situations. Although they are theoretical, they have been developed in

Table 2. Overview of considered networks and systems relevant to fulfillment of ODD requirements.

Network	Description	Length (km)	System available: ODD infrastructure and conditions requirements are met	System available: Only ODD infrastructure requirements are met	System available: ODD requirements are not met
1. Motorway/dual carriageway roads	All motorway and dual carriageway roads (driving lanes totally separated)	1,104	Motorway ADS	ESC, AEB	-
2. Level I main roads	Remaining main highway stretches (Level I).	2,519	-	-	ESC, AEB
3. Other main roads	Main highways (Level II) and other main roads	9,829	-	-	ESC, AEB
4. Main street network in largest cities	Main streets in the metropolitan area and the city of Turku.	292	Urban ADS	ESC, AEB	-
5. Other street network in largest cities	Collector and local streets in corresponding cities.	597	-	-	ESC, AEB

collaboration with ADS developers and can thus be expected to represent a reasonable version of a future mature product. These mature systems keep the vehicle in lane and maintain a safe distance to the vehicles in front. When the ODD requirements are about to be violated a takeover request is given to the driver, who is required to take back control of the vehicle. The target speed of ADS is the speed limit, but at most 130 km/h on motorways. It should be noted that the ADS function includes AEB and ESC functionalities.

The vehicle's advanced ADS-related equipment can enable ADAS support for manual driving. The study was limited to AEB and electronic stability control (ESC) since these are intervening active systems and do not require a reaction or intervention from the driver. AEB detects upcoming hazards and, if needed, automatically brakes to avoid or mitigate a collision (Euro NCAP, 2021). ESC improves stability and traction by applying brakes automatically when detecting loss of control. The current vehicle fleet penetration in Finland for AEB is 4% for rural roads and 7% for urban roads, and 60% for ESC (Lähderanta, 2018).

Identification of networks under assessment

The network for each ADS was identified based on the system descriptions. The operating road network for motorway ADS includes all motorway and dual-carriageway road sections from the national road statistics (FTIA, 2020).

The network for urban ADS includes the main streets in the metropolitan area (1.2 M inhabitants)—constituting the cities of Helsinki, Espoo, and Vantaa—and the city of Turku (193,000 inhabitants) (Statistics Finland, 2020a). These were selected because they are the major cities of Finland, making up 25% of the total population. They also have an extended street network, maximizing the potential for using urban ADS. The main streets were identified from the individual cities' street network hierarchies (City of Espoo, 2020; City of Helsinki, 2010; City of Turku, 2020; City of Vantaa, 2020).

When the ODD requirements related to conditions are not fulfilled, AEB and ESC remain enabled on the ADS networks (motorway/dual carriageways and main street network). Furthermore, AEB and ESC are expected to be enabled on main roads and the other street network. The main roads were limited to two separate networks: i) "Level I main roads" and ii) "Other main roads," and these differ substantially. The Level I main road network is, except for physically separated driving directions, similar to the motorway network in terms of high quality and regular maintenance, speed limits of at least 80 km/h, regular provision of safe overtaking opportunities, and limited number of intersections (FTIA, 2019). The other main road network includes the remaining main road stretches maintained by the Finnish Transport Agency. The other street network entails the remaining street network (collector and local streets) in the respective cities. ESC and AEB are not similarly subject to limiting conditions; thus, in practice, they could also be used on e.g., private roads, but the networks under assessment had to be limited to sections for which the necessary input data was available. The assessed networks are also those where ADS will most likely be introduced and where ADS can be expected to be of greatest use (main road network and largest cities).

Table 3. Share of injury crashes occurring in road and weather conditions fulfilling ADS' ODD requirements related to conditions of all injury crashes on Finnish main roads.

Categories		Share of injury crashes (%)	Total share of injury crashes (%)
Road condition[1]	Dry road surface	47.15	69.5
	Moist road surface	10.70	
	(Other) normal driving conditions	11.67	
Weather condition[1]	Overcast	24.75	84.3
	Cloudy	17.91	
	Clear	13.40	
	Partly cloudy	11.37	
	Mostly clear	8.94	
	Overcast and light rain	6.69	
	Cloudy and light rain	1.01	
	Partly cloudy and light rain	0.12	
	Mostly clear and light rain	0.06	
	Clear and light rain	0.01	

[1]Categories defined by data provider Foreca Ltd.

Table 2 summarizes the road networks considered and the respective systems for situations in which both infrastructure- and condition-related ODD requirements and infrastructure-only requirements are fulfilled.

Calculation of the current safety situation

The current safety situation was calculated with the methodology described by Peltola et al. (2013, 2019). The expected number of injury crashes (*ICe*) is calculated with the EB method by combining two predictions: the injury crash record (*ICr* = annual average number of injury crashes) and the injury crash prediction model (*ICm*). The expected number of serious injuries (SI) is calculated by multiplying the expected number of injury crashes by the average SI severity (average number of SI/100 injury crashes), and the expected number of fatalities is calculated by multiplying the expected number of SI by the average share of fatalities per SI. The average severities are calculated per road type. The injury crash prediction model is calculated as follows:

$$IC_m = \ e^C x \ ADT^B x \ Mileage \quad (1)$$

Where C is a constant (value depending on crash type) and B is a coefficient used to calculate the traffic volume-dependent coefficient (value depends on road type). The predictions are then combined as follows:

$$IC_e = A \ x \ IC_m + (1 - A) \ x \ IC_r \quad (2)$$

where A is a weight factor and is calculated as follows:

$$A = \frac{K}{K + IC_m} \quad (3)$$

and where K is the inverse value of the over-dispersion parameter and is estimated with generalized linear models.

Since the TARVA tool currently only covers the main road network, the methodology of Peltola et al. (2013, 2019) was further developed and extended to urban areas so that the current safety situation on all assessed networks is calculated similarly. First, the considered cities' street networks centerline and traffic volume (average daily traffic volume/link) data were combined. Second, homogeneous line sections were computed by merging comparable road links (in terms of e.g., street name and functional class) and calculating a link-length weighted kilometrage (vehicle kilometers driven) for each section. Third, 5-year (2014–2018) crash data (Statistics Finland, 2020b) were linked to the homogeneous road line sections based on coordinates. Fourth, the required data (length, mileage, injury crash record (*ICr*)) for calculations for each road line section per speed limit zone ($\leq$ 40 km/h and $\geq$ 50 km/h) were compiled. Fifth, the crash prediction model (*ICm*, Equation 1) was calculated (with SPSS Software) by fitting a generalized linear model, with Poisson error distribution and log link function, for each road section and crash type per speed limit zone. Finally, the expected number of crashes (*ICe*) was calculated by combining the two predictions (Equation 2) with the calculated A (Equation 3) for each road line section and crash type per speed limit zone.

Limitations from road and weather conditions

The share of injury crashes occurring in road and weather conditions fulfilling ODD requirements were identified from the results of a previous project (Malin et al., 2017; 2019) representing measured detailed road and weather conditions at the time of the crash as opposed to post-coded general road and weather condition categories available in the national crash statistics. The weather and road condition

Table 4. Share (%) of all crashes belonging to the target crash types of AEB and ESC for different networks.

	Motorway			Main roads			Urban areas		
	All injury crashes	Fatal crashes	Serious injury crashes	All injury crashes	Fatal crashes	Serious injury crashes	All injury crashes	Fatal crashes	Serious injury crashes
TCT_{AEB}	37.4	21.9	21.2	27.5	7.2	18.0	41.5	38.5	35.4
TCT_{ESC}	45.7	37.5	59.6	36.6	20.3	33.5	10.9	25.0	20.7

categories (Malin et al., 2017) were classified according to the condition-related ODD requirements (Table 1). Table 3 lists the categories fulfilling the ODD requirements and the share of all injury crashes occurring in these conditions. Of the injury crashes, 69.5% occurred in road conditions fulfilling the ODD requirements, whereas the corresponding share of weather conditions was 84.3%.

Identification of crashes potentially affected by active safety systems

To identify crashes which can potentially be affected by AEB and ESC in locations where the ODD requirements are not fulfilled, the considered systems' target crash types were first identified based on previous research results. The AEB target crash types for motorways and main roads were: rear-end, hitting a fixed object, angle collision, and animal crash; and for urban areas: rear-end, hitting a fixed object, pedestrian, right turn, and angle collision (Høye, 2011; Wang et al., 2020). The ESC target crash type was single-vehicle crashes (roll-over, run-off). Of all Finnish road crashes, the share of crashes belonging to the target crash types (TCT) were calculated separately for motorways, main roads, and urban areas (main and other street network) (Statistics Finland, 2020b) (Table 4). The calculations were done separately for all injury, fatal, and serious injury crashes.

Calculation of potentially affected crashes overall

The potentially affected crashes (*PAC*) per considered ADS were calculated by multiplying the current safety situation on the respective operating network by the share of limiting road conditions (*RC*) and the share of limiting weather conditions (*WC*). The calculations were done for the number of injury crashes, fatalities, and serious injuries.

$$PAC_{ADF,s} = Current\ \ safety\ \ situation_s * Limiting\ \ RC * Limiting\ \ WC \quad (4)$$

where *s* is severity. For AEB and ESC, the potentially affected crashes were calculated by multiplying the current safety situation (subtracted by PAC_{ADS} on the networks: motorway/dual carriageway and main street network in the largest cities) by each system's share of target crash types (*TCT*) (Table 4) and remaining vehicle fleet penetration (*RP*) (*RP = 1 - current vehicle fleet penetration* (see page 8) on the respective network.

$$PAC_{AEB+ESC} = Current\ \ safety\ \ situation_s\ *TCT_{AEB}\ *RP_{AEB} + Current\ \ safety\ \ situation_s * TCT_{ESC}\ *RP_{ESC} \quad (5)$$

where *s* is severity. The crashes potentially affected by AEB and ESC were summed up, since they have different target crash types.

To calculate the scope of impact, i.e., the fraction of crashes potentially affected by the systems, the number of potentially affected injury crashes, fatalities, and serious injuries was compared with the annual average (2014–2019) for the whole country (Statistics Finland, 2020b): 5,816 injury crashes, 241 fatalities, and 470 serious injuries. For urban ADS, the number of potentially affected crashes was also compared to the annual average (2014–2018) of the selected four cities (Statistics Finland, 2020b): 727 injury crashes, 15.4 fatalities, and 44.6 serious injuries.

Results

Current safety situation

The current safety situation on different road networks is outlined in Table 5. Compared to the "Total on main road networks," the risks are higher on other main roads (injury crash 28%; fatality 52%; serious injury 47%) and Level I main roads (injury crash 9%; fatality 31%; serious injury 24%). The corresponding risks for motorway and other dual carriageway roads are lower for all severities (31–69%). Compared to the "Total in urban areas," the risk on other streets is higher (22–24%) and on main streets lower (19–21%) for all severities. Compared to the "Total on all networks," the risks of an injury crash and serious injury are by far the highest on urban street networks—more than double on main streets and over threefold on other streets. The fatality risk, on the other hand, is highest (56%) on the network other main roads. Compared to the "Total on all networks," the risks are lower on motorways and other dual

Table 5. Overview of the current safety situation on different networks.

	Network	Length (km)	Mileage (Mkm/y)	Annual number (No./year) Injury crashes	Fatalities	Serious injuries	Risk (No./Mkm) Injury crashes	Fatalities	Serious injuries
Main road network	Motorway/dual carriageway roads	1,104	10,011	326	12.9	25.5	0.0326	0.0013	0.0025
	Level I main roads	2,519	6,544	336	36.2	47.1	0.0513	0.0055	0.0072
	Other main roads	9,829	8,968	543	57.2	76.6	0.0605	0.0064	0.0085
	Total on main road networks	*13,452*	*25,523*	*1,205*	*106.3*	*149.2*	*0.0472*	*0.0042*	*0.0058*
Urban areas	Main street network in largest cities	292	1,489	216	4.5	20.4	0.1451	0.0030	0.0137
	Other street network in largest cities	597	1,238	270	5.8	25.9	0.2181	0.0047	0.0209
	Total in urban areas	*889*	*2,727*	*486*	*10.3*	*46.3*	*0.1782*	*0.0038*	*0.0170*
	Total on all networks	14,341	28,250	1,691	116.6	195.5	0.0599	0.0041	0.0069

carriageways for all severities (46–68%), other main roads for injury accidents (14%) and the main street network for fatalities (27%).

Crashes potentially affected by ADS

Potentially, motorway ADS can affect annually 191 injury crashes, eight fatalities, and fifteen serious injuries, which corresponds to 3.3% of all injury crashes, 3.1% of all fatalities, and 3.2% of all serious injuries in Finland (Table 6). In the four largest cities in Finland, urban ADS can potentially affect annually 127 injury crashes, three fatalities, and twelve serious injuries. Compared to the country's annual average, this corresponds to 2.2% of injury crashes, 1.1% of fatalities, and 2.5% of serious injuries. Compared to the selected cities' annual average, this corresponds to 17.4% of injury crashes, 17.1% of fatalities, and 26.8% of serious injuries.

Crashes potentially affected by AEB and ESC

Active safety systems working when the ODD requirements of motorway ADS are not fulfilled can affect annually 643 injury crashes, 21 fatalities, and 62 serious injuries (Table 7). This corresponds to 11.1% of all injury crashes, 8.6% of all fatalities, and 13.2% of all serious injuries in Finland. Considering both the motorway ADS and the selected active safety systems, they could potentially affect 14.3% of all injury crashes, 11.7% of all fatalities, and 16.4% of all serious injuries in Finland.

Active safety systems working when the ODD requirements of urban ADS are not fulfilled can affect annually 693 injury crashes, 25 fatalities, and 66 serious injuries (Table 8). This corresponds to 11.9% of all injury crashes, 10.2% of all fatalities, and 14.0% of all serious injuries in Finland. Considering both the urban ADS and the selected active safety systems, they could potentially affect 14.1% of all injury crashes, 11.3% of all fatalities, and 16.6% of all serious injuries in Finland.

Discussion

This study identified the crashes that may potentially be affected by conditionally automated vehicles (SAE3) based on the current annual expected number of injury crashes, fatalities, and serious injuries on different road networks in Finland. To model the current safety situation on all networks similarly, the methodology of Peltola et al. (2013, 2019) was further developed and extended to cover also urban areas.

When comparing the current safety situation on the different main road networks, the risk of crashes (No./Mkm) of all severities was higher on the network of other main roads (28–52%) and Level I main roads (9–31%) for all severities than on "Total on main road networks." The corresponding risks were lower on motorways and other dual carriageways (31–69%) for all severities. Compared to the "Total in urban areas," the risk was higher on other streets (22–24%) and lower on main streets (19–21%) for all severities. In other words, the current safety situation is best on the networks where ADS would be used (motorway and dual carriageways; main streets) as compared to other networks (Level I main roads; other main roads; other streets). For the two urban networks the risks were, however, higher (with the risk for injury crash and serious injury being more than double) than the "Total on all networks." These findings are in line with previous research suggesting that safety in urban areas has improved at a slower rate than on motorways (Elvik, 2010). Furthermore, consistently with Malin et al. (2020), it highlights the importance of urban areas when working toward the goal of reducing serious injuries.

Of the national annual average, motorway ADS has the potential to affect at maximum 3.3% of injury crashes, 3.1% of fatalities, and 3.2% of serious injuries. These results are in line with Rösener's (2020) finding that a similar system could address 3% of all injury crashes in Germany, and with Bjorvatn et al.'s (2021) finding that the same system could address potentially at most 4.4% of slight injury crashes, 4.1% of fatalities, and 3.1% of serious injury crashes in the EU27 + 3.

Table 6. Number and share (compared to the national[1] and selected cities'[2] annual average) of crashes potentially affected by ADS.

	Motorway ADS, used on all motorways			Urban ADS, used in four largest cities		
	Injury crashes	Fatalities	Serious injuries	Injury crashes	Fatalities	Serious injuries
Number of potentially affected crashes	*191*	*7.6*	*14.9*	*127*	*2.6*	*11.9*
Share (national annual average[1]) of potentially affected crashes	**3.3%**	**3.1%**	**3.2%**	**2.2%**	**1.1%**	**2.5%**
Share (selected cities' annual average[2]) of potentially affected crashes	-	-	-	**17.4%**	**17.2%**	**26.8%**

[1]*5,816 injury crashes; 241 fatalities; 470 serious injuries (*Statistics Finland, 2020b*).*
[2]*727 injury crashes; 15.4 fatalities; 44.6 serious injuries (*Statistics Finland, 2020b*).*

Table 7. Number and share (compared to the national annual average) of crashes potentially affected by motorway ADS.

		ADS (when ODD requirements are met)			*AEB + ESC* (when ODD requirements are not met)			*ADS* (when ODD requirements are met) + *AEB + ESC* (when ODD requirements are not met)		
	Network	Injury crashes	Fatalities	Serious injuries	Injury crashes	Fatalities	Serious injuries	Injury crashes	Fatalities	Serious injuries
Number of potentially affected crashes	**Motorway/dual carriageway roads**	*191*	*7.6*	*14.9*	*73*	*1.9*	*4.7*	*834*	*28.2*	*77*
	Level I main roads	–	–	–	*138*	*5.5*	*14.4*			
	Other main roads	–	–	–	*223*	*8.6*	*23.5*			
	Main street network in largest cities	–	–	–	*93*	*1.9*	*8.8*			
	Other street network in largest cities	–	–	–	*116*	*2.7*	*10.7*			
	Total	**191**	**7.6**	**14.9**	**643**	**20.6**	**62.1**	**834**	**28.2**	**77**
Share (compared to national annual average[1]) of potentially affected crashes		**3.3%**	**3.1%**	**3.2%**	**11.1%**	**8.6%**	**13.2%**	**14.3%**	**11.7%**	**16.4%**

[1]*5,816 injury crashes; 241 fatalities; 470 serious injuries (*Statistics Finland, 2020b*).*

Table 8. Number and share (compared to the national annual average) of crashes potentially affected by urban ADS used in the four largest cities in Finland.

		ADS (when ODD requirements are met)			*AEB + ESC* (when ODD requirements are not met)			*ADS* (when ODD requirements are met) + *AEB + ESC* (when ODD requirements are not met)		
	Network	Injury crashes	Fatalities	Serious injuries	Injury crashes	Fatalities	Serious injuries	Injury crashes	Fatalities	Serious injuries
Number of potentially affected crashes	**Motorway/dual carriageway roads**	–	–	–	*177*	*7.0*	*13.8*	*820*	*27.4*	*77.8*
	Level I main roads	–	–	–	*138*	*5.5*	*14.4*			
	Other main roads	–	–	–	*223*	*8.6*	*23.5*			
	Main street network in largest cities	*127*	*2.7*	*11.9*	*39*	*0.9*	*3.5*			
	Other street network in largest cities	–	–	–	*116*	*2.7*	*10.7*			
	Total	127	2.7	11.9	*693*	*24.7*	*65.9*	820	27.4	77.8
Share (compared to national annual average[1]) of potentially affected crashes		**2.2%**	**1.1%**	**2.5%**	**11.9%**	**10.2%**	**14.0%**	**14.1%**	**11.3%**	**16.6%**

[1]*5,816 injury crashes; 241 fatalities; 470 serious injuries (*Statistics Finland, 2020b*).*

Currently, the use of motorway ADS in Finland would be severely restricted by the requirement for physically separated driving directions, given that roughly only 1.5% of the main road network is physically separated and the rest is mostly single carriageway roads. Should the development of ADS technology move toward including high-level rural roads, such as Level I main roads, in their ODD, the operating environment of this technology could be substantially extended.

The use of urban ADS in the four largest cities has the potential to affect a maximum of 2.2% of injury crashes, 1.1% of fatalities, and 2.5% of serious injuries of the overall annual average in Finland. Compared to the annual average of the selected cities in this study, urban ADS has the potential to affect 17.4% of injury crashes, 17.1% of fatalities, and 26.8% of serious injuries. The results are considerably smaller than Rösener's (2020), who found that an Urban Robo-Taxi could address 46% of all injury crashes in Germany, and Bjorvatn et al.'s (2021) finding that the same urban ADS as used in this study could address potentially at maximum 43% of slight injury crashes, 18% of fatalities, and 33% of serious injury crashes in the EU27 + 3. The differences may relate to Rösener's system being more advanced (SAE4 and no restricting conditions) and the estimates in both studies being based on data on all crashes that took place in urban areas regardless of the size of the urban area, hence extending the assessment to all urban areas in the country. The differences may also relate to country-specific differences in terms of prevalence and sizes of urban areas. Data availability limited our analysis to the four largest cities in Finland. Future studies should, therefore, consider how the results can be applied to other urban areas in Finland. In all, it seems that urban ADS has greater safety potential than motorway ADS, but its development still lags behind the systems designed for motorways due to its more complex operating environment.

If considering that AEB and ESC are working also whenever the ODD requirements of ADS are not fulfilled, motorway ADS could potentially affect 14.3% of all injury crashes, 11.7% of all fatalities, and 16.4% of all serious injuries in Finland whereas the corresponding fractions for use of urban ADS in the four largest cities are 14.1%, 11.3%, and 16.6%. The analysis on complementing active safety systems was limited to AEB and ESC, since these do not require a reaction or intervention from the driver. In practice, the sensor and camera technology in new vehicles also supports the use of other ADAS. Hence, our fraction of potentially affected crashes for ADAS is somewhat conservative; their potential is likely to be greater.

The study did not consider the effectiveness of ADS in preventing or mitigating these potentially affected crashes, nor potential penetration rates for these systems. Bjorvatn et al. (2021) found that motorway ADS improves safety effectively when the ODD requirements are fulfilled, but since the motorway network is limited and its safety level is already pretty good, the total safety effect (of all injury crashes) is limited (0.1–1.2% with a penetration rate of 5–30%). Furthermore, there could be a change in crash causation (e.g., severity and crash type) rather than avoiding crashes entirely.

As opposed to previous similar studies (Combs et al., 2019; Utriainen, 2021; Wang et al., 2020), our assessment was based on the expected number of crashes, as they better estimate the current safety situation by eliminating random variation of crash records (e.g., Elvik, 2008). Using the expected number of crashes is an especially important feature when investigating different crash severities, as it entails dividing crash records into even smaller groups. Furthermore, to our knowledge, this is the first study applying the expected number of crashes with the EB method as a basis for safety evaluation of automated vehicles. To calculate the fraction of potentially affected crashes, the number of potentially affected crashes was proportioned to the overall national average over 5–6 years, which is justifiable because the networks for the systems were clearly defined. Due to data availability, the urban ADS analysis was limited to the four largest cities, and as a result, the urban ADS was also proportioned to the selected cities' annual average. However, urban ADS could be used also in other cities than those included in the estimate, indicating that the potential could be substantially greater. Nevertheless, the analysis includes those cities where the ADS can be expected to be of greatest use.

The limitations of weather and road conditions were based on a previous project (Malin et al., 2017; 2019) investigating the main road network. Thus, directly applying these results to the different road networks established in this study poses some uncertainties in our results. These results were nevertheless used in this study, as they represent measured conditions at the time of the crash as opposed to post-coded information in the national crash statistics. Also, the data of Malin et al. contained more detailed road and weather condition categories than those given in the national crash statistics, enabling a more precise estimate of the share of crashes occurring in conditions fulfilling the ODD requirements.

Future research should be done to estimate the traffic safety effects of ADS, since this study only assessed the number and national fraction of potentially affected crashes in the current situation. The analysis did not separately consider usage or deployment scenarios of AVs. Hence, the results only indicate the full potential of the considered ADS. All in all, motorway ADS has the potential to affect at maximum 3.3% of injury crashes, 3.1% of fatalities, and 3.2% of all serious injuries in Finland. The corresponding fractions for urban ADS in the four largest Finnish cities were: 2.2%, 1.1% and 2.5%. Of the cities' annual average, urban ADS has the potential to affect at the most 17.4% of injury crashes, 17.1% of fatalities, and 26.8% of serious injuries. Furthermore, the networks where the ADS work are the ones where the current safety situation is the best. Although market introduction of ADS is on the horizon, deployment can be expected to be slow especially in Finland, which has one of the slowest renewing vehicle fleets in Europe. This suggests that additional measures should be implemented to reach the traffic safety goals, even though conditional automation is likely to contribute to it once it is in use.

Acknowledgments

This paper results from the L3Pilot project. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 723051. The sole responsibility of this publication lies with the authors. The authors would like to thank all the partners within L3Pilot for their cooperation and valuable contribution. We would also wish to thank Miloš N. Mladenović for his helpful comments on an earlier draft of the manuscript, and Adelaide Lönnberg (MapleMountain Editing) for reviewing the language.

Declaration of interest statement

The authors report there are no competing interests to declare.

Funding

European Commission Horizon 2020 program, L3Pilot, grant agreement no. 723051.

ORCID

Fanny Malin http://orcid.org/0000-0002-8042-7981
Anne Silla http://orcid.org/0000-0001-8862-2194
Johannes Mesimäki http://orcid.org/0000-0002-3001-4572
Satu Innamaa http://orcid.org/0000-0002-2752-5881
Harri Peltola http://orcid.org/0000-0001-5160-3563

Data availability statement

The crash data used in this study were used solely with permission for the current study and are therefore not publicly available. The crash data can be requested from Statistics Finland.

The traffic volume data were used solely with permission for the current study and are therefore not publicly available. The data can be requested from the cities' representatives.

References

Bjorvatn, A., Page, Y., Weber, H., Aittoniemi, E., Fahrenkrog, F., Hermitte, T., Heum, P., Hiller, J., Innamaa, S., Itkonen, T., Lehtonen, E., Malin, F., Silla, A., Sintonen, H., Streubel, T., & Torrao, G. (2021). *L3Pilot deliverable 7.4: Impact evaluation results.* Horizon 2020 ART-02-2016. Automation pilots for passenger cars. Retrieved January 14, 2021, from https://l3pilot.eu/fileadmin/user_upload/Downloads/Deliverables/Update_14102021/L3Pilot-SP7-D7.4-Impact_Evaluation_Results-v1.0-for_website.pdf

City of Espoo. (2020). Autoliikennemäärät Espoossa 2019 [Traffic volume in Espoo in 2019]. Retrieved December 3, 2020, from https://www.espoo.fi/download/noname/%7B3B4BE5F7-A047-48A4-B94A-DD047271F46E%7D/126397

City of Helsinki. (2010). Katuverkon luokittelu. Nykytila. [Hierarchy of street network. Current situation]. Retrieved December 3, 2020, from https://dev.hel.fi/paatokset/media/att/2e/2e609ebaeda0f8c73a3591145728ca-c67ac71db8.pdf

City of Turku. (2020). Liikennemääräkartta 2020. [Traffic volume map 2020].

City of Vantaa. (2020). Vantaan karttapalvelu. Katujen toiminnalliset luokat. [Vantaa Map Service. Functional class of streets]. Retrieved December 3, 2020, from https://kartta.vantaa.fi/

Combs, T. S., Sandt, L. S., Clamann, M. P., & Mc Donald, N. C. (2019). Automated vehicles and pedestrian safety: Exploring the promise and limits of pedestrian detection. *American Journal of Preventive Medicine*, *56*(1), 1–7. https://doi.org/10.1016/j.amepre.2018.06.024

EC. (2020a). EU road safety policy framework 2021–2030. Next steps towards 'Vision Zero'. Commission Staff Working Document SWD (2019) 283 final. Retrieved February 1, 2021, from https://ec.europa.eu/transport/sites/transport/files/legislation/swd20190283-roadsafety-vision-zero.pdf

EC. (2020b). Sustainable and Smart Mobility Strategy –putting European transport on track for the future. COM(2020) 789 final. Retrieved February 1, 2021, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

Elvik, R. (2008). The predictive validity of empirical Bayes estimates of road safety. *Accident; Analysis and Prevention*, *40*(6), 1964–1969. https://doi.org/10.1016/j.aap.2008.07.007

Elvik, R. (2010). Why some road safety problems are more difficult to solve than others. *Accident; Analysis and*

Prevention, *42*(4), 1089–1096. https://doi.org/10.1016/j.aap.2009.12.020

Elvik, R., Høye, A., Vaa, T., & Sørensen, M. (2009). *The handbook of road safety measures* (2nd ed.). Emerald Group Publishing Limited.

ERTRAC. (2017). Automated driving roadmap. Retrieved February 1, 2021, from: https://www.ertrac.org/uploads/images/ERTRAC_Automated_Driving_2017.pdf

Euro NCAP. (2021). Glossary. Retrieved February 1, 2021, from: https://www.euroncap.com/en/vehicle-safety/glossary/#

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Favaró, F. M., Nader, N., Eurich, S. O., Tripp, M., & Varadaraju, N. (2017). Examining accident reports involving autonomous vehicles in California. *PLoS ONE*, *12*(9), e0184952. https://doi.org/10.1371/journal.pone.0184952

FTIA. (2019). Pääteiden palvelutaso ja tulevaisuuden tarpeet. *[Service level and future needs of main public highways]* Finnish Transport Infrastructure Agency. Retrieved February 1, 2021, from https://vayla.fi/documents/25230764/0/P%c3%a4%c3%a4teiden±palvelutaso±ja±tulevaisuuden±tarpeet_Raportti_05.11.2019.pdf/16d2427b-34cb-4a93-be78-bcef49a7a1ed

FTIA. (2020). Road register. Retrieved February 1, 2021, from https://extranet.vayla.fi/web/extranet/

Furlan, A. D., Kajaks, T., Tiong, M., Lavallière, M., Campos, J. L., Babineau, J., Haghzare, S., Ma, T., & Vrkljan, B. (2020). Advanced vehicle technologies and road safety: A scoping review of the evidence. *Accident; Analysis and Prevention*, *147*, 105741. https://doi.org/10.1016/j.aap.2020.105741

Hauer, E., Harwood, D. W., Council, F. M., & Griffith, M. S. (2002). Estimating safety by the empirical Bayes method. A tutorial. In *Transportation research record* (vol. 1784, pp. 126–131). Transportation Research Board.

Høye, E. (2011). The effects of Electronic Stability Control (ESC) on crashes-an update. *Accident; Analysis and Prevention*, *43*(3), 1148–1159. https://doi.org/10.1016/j.aap.2010.12.025

Innamaa, S., Smith, S., Barnard, Y., Rainville, L., Rakoff, H., Horiguchi, R., & Gellerman, H. (2018). Trilateral impact assessment framework for automation in road transportation. Retrieved December 3, 2020, from https://connectedautomateddriving.eu/publication/trilateral-impact-assessment-framework-for-automation-in-road-transportation-2/

Kitajima, S., Shimono, K., Tajima, J., Antona-Makoshi, J., & Uchida, N. (2019). Multi-agent traffic simulations to estimate the impact of automated technologies on safety. *Traffic Injury Prevention*, *20*(sup1), S58−–64. https://doi.org/10.1080/15389588.2019.1625335

Lähderanta, T. (2018). Kuljettajien tukijärjestelmien yleistyminen Suomessa [Deployment of driver support systems in Finland]. Trafi Publications 22/2018. Finnish Transport Safety Agency. Helsinki.

Malin, F., Norros, I., & Innamaa, S. (2017). *Identification of accident risk and its application in traffic control. Accident risks in different road weather conditions on Finnish main roads*. Research reports of the Finnish Transport Agency 41/2017. Finnish Transport Agency.

Malin, F., Norros, I., & Innamaa, S. (2019). Accident risk of road and weather conditions on different road types. *Accident; Analysis and Prevention*, *122*, 181–188. https://doi.org/10.1016/j.aap.2018.10.014

Malin, F., Silla, A., & Mladenović, M. (2020). Prevalence and factors associated with pedestrian fatalities and serious injuries: case Finland. *European Transport Research Reiew*, *12*, 29. https://doi.org/10.1186/s12544-020-00411-z

Metz, B., Rösener, C., Louw, T., Aittoniemi, E., Bjorvatn, A., Wörle, J., Weber, H., Torrao, G. A., Silla, A., Innamaa, S., Malin, F., Lehtonen, E., Fahrenkrog, F., Heum, P., Pedersen, K., Merat, N., Nordhoff, S., Beuster, A., Dotzauer, M., & Streubel, T. (2019). *Evaluation methods*, Deliverable 3.3. of L3Pilot project.

Milakis, D., van Arem, B., & van Wee, B. (2017). Policy and society related implications of automated driving: A review of literature and directions for future research. *Journal of Intelligent Transportation Systems*, *21*(4), 4, 324–348. https://doi.org/10.1080/15472450.2017.1291351

Morando, M. M., Tian, Q., Truong, L. T., & Vu, H. L. (2018). Studying the safety impact of autonomous vehicles using simulation-based surrogate safety measures. *Journal of Advanced Transportation, Article ID 6135183*, *2018*, 1–11. https://doi.org/10.1155/2018/6135183

Noy, I. Y., Shinar, D., & Horrey, W. J. (2018). Automated driving: safety blind spots. *Safety Science*, *102*, 68–78. https://doi.org/10.1016/j.ssci.2017.07.018

Papadoulis, A., Quddus, M., & Imprialou, M. (2019). Evaluating the safety impact of connected and autonomous vehicles on motorways. *Accident; Analysis and Prevention*, *124*, 12–22. https://doi.org/10.1016/j.aap.2018.12.019

Peltola, H., Rajamäki, R., & Luoma, J. (2013). A tool for safety evaluations of road improvements. *Accident; Analysis and Prevention*, *60*, 277–288. https://doi.org/10.1016/j.aap.2013.04.008

Peltola, H., Ristikartano, J., Malin, F., & Heikkilä, K. (2019). *Serious injuries in the estimation tools of Finnish Transport Infrastructure Agency*. Publications of the Finnish Transport Infrastructure Agency 33/2019. Finnish Transport Infrastructure Agency.

Rösener, C. (2020). *A traffic-based method for safety impact assessment of road vehicle automation*. [Doctoral dissertation]. RWTH Aachen University.

SAE International. (2021). Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. https://doi.org/10.4271/J3016_202104

Scanlon, J. M., Kusano, K. D., Daniel, T., Alderson, C., Ogle, A., & Victor, T. (2021). Waymo simulated driving behavior in reconstructed fatal crashes within an autonomous vehicle operating domain. *Accident; Analysis and Prevention*, *163*, 106454. https://doi.org/10.1016/j.aap.2021.106454

Scholliers, J., Tarkiainen, M., Silla, A., Modijefsky, M., Janse, R., & van den Born, G. (2020). *Study on the feasibility, costs and benefits of retrofitting advanced driver assistance to improve road safety*. European Commission, Directorate-General for Mobility and Transport, Brussels.

Statistics Finland. (2020a). *Population*. Retrieved February 1, 2021, from: https://www.tilastokeskus.fi/tup/suoluk/suoluk_vaesto_en.html

Statistics Finland. (2020b). *Statistics on road traffic accidents*. Retrieved December 3 2020 from: http://tilastokeskus.fi/til/ton/index_en.html.

Utriainen, R. (2021). Potential impacts of automated vehicles on pedestrian safety in a four-season country. *Journal of Intelligent Transportation Systems*, *25*(2), 188–196. https://doi.org/10.1080/15472450.2020.1845671

Utriainen, R., & Pöllänen, M. (2020). Prioritizing safety or traffic flow? Qualitative study on highly automated vehicles' potential to prevent pedestrian crashes with two different ambitions. *Sustainability*, *12*(8), 3206. https://doi.org/10.3390/su12083206

Valletta Declaration on Road Safety. (2017). *Ministerial declaration on road safety*. 29, March. Valletta Malta EU2017.

Virdi, N., Grzybowska, H., Waller, S. T., & Dixit, V. (2019). A safety assessment of mixed fleets with connected and autonomous vehicles using the surrogate safety assessment module. *Accident; Analysis and Prevention*, *131*, 95–111. https://doi.org/10.1016/j.aap.2019.06.001

Wang, S., & Li, Z. (2019). Exploring the mechanism of crashes with automated vehicles using statistical modelling approaches. *PLoS ONE*, *14*(3), e0214550. https://doi.org/10.1371/journal.pone.0214550

Wang, L., Zhong, H., Ma, W., Abdel-Aty, M., & Park, J. (2020). How many crashes can connected vehicle and automated vehicle technologies prevent: A meta-analysis. *Accident; Analysis and Prevention*, *136*, 105299. https://doi.org/10.1016/j.aap.2019.105299

Wang, L., Fahrenkrog, F., Vogt, T., Jung, O., & Kates, R. (2017). Prospective safety assessment of highly automated driving functions using stochastic traffic simulation. 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV): Innovations in Vehicle Safety: Opportunities and Challenges. 5 – 8 June, 2017, Detroit Michigan, United States. Retrieved February 1, 2021, from http://indexsmart.mirasmart.com/25esv/PDFfiles/25ESV-000224.pdf

Yannis, G., Papadimitriou, E., Chaziris, A., & Broughton, J. (2014). Modeling road accident injury under-reporting in Europe. *European Transport Research Review*, *6*(4), 425–438. https://doi.org/10.1007/s12544-014-0142-4

Ye, W., Wang, C., Chen, F., Yan, S., & Li, L. (2021). Approaching autonomous driving with cautious optimism: Analysis of road traffic injuries involving autonomous vehicles based on field test data. *Injury Prevention*, *27*(1), 42–47. https://doi.org/10.1136/injuryprev-2019-043402